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RESEARCH MEMORANDUM

PERFORMANCE EVALUATION OF REDUCED-CHORD ROTOR BLADING AS APPLIED TO J73 TWO-STAGE TURBINE

III - OVER-ALL PERFORMANCE OF FIRST-STAGE TURBINE WITH STANDARD ROTOR BLADES AT INLET CONDITIONS OF 35 INCHES OF MERCURY ABSOLUTE AND 700° R

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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By Harold J. Schum

SUMMARY

The multistage turbine from the J73 turbojet engine has previously been investigated with standard and with reduced-chord rotor blading in order to determine the individual performance characteristics of each configuration over a range of over-all pressure ratio and speed. Because both turbine configurations exhibited peak efficiencies of over 90 percent, and because both units had relatively wide efficient operating ranges, it was considered of interest to determine the performance of the first stage of the turbine as a separate component. Accordingly, the standard-bladed multistage turbine was modified by removing the second-stage rotor disk and stator and altering the flow passage so that the first stage of the unit could be operated independently. The modified single-stage turbine was then operated over a range of stage pressure ratio and speed.

The single-stage turbine operated at a peak brake internal efficiency of over 90 percent at an over-all stage pressure ratio of 1.4 and at 90 percent of design equivalent speed. Furthermore, the unit operated at high efficiencies over a relatively wide operating range. When the single-stage results were compared with the multistage results at the design operating point, it was found that the first stage produced approximately half the total multistage-turbine work output.

INTRODUCTION

The performance of the two-stage turbine from the J73 turbojet engine is being investigated at the NACA Lewis laboratory. Reference 1

[1] The information presented herein was previously given limited distribution.

[redacted]

presented the over-all performance of the turbine operating as a component at an inlet pressure of 35 inches of mercury absolute and an inlet temperature of 700° R over a range of speed and pressure ratio. A saving in component weight was then effected by replacing the standard turbine rotors with a configuration utilizing reduced-chord rotor blades; the performance of this unit is reported in reference 2. Comparison of the performance results of the two turbine configurations indicated no significant reduction in performance with the use of reduced-chord rotor blades, although the weight of the rotor disk and blades was reduced over 40 percent. 3209

Both multistage turbine configurations exhibited efficiencies of over 90 percent at the design operating point. Furthermore, both turbines operated at high efficiencies over a wide range of speeds and pressure ratios. It was considered of interest, then, to ascertain the performance of the first stage of the turbine when operated as a component. Accordingly, the standard-bladed multistage turbine was modified by removing the second-stage rotor and stator and making appropriate changes in the flow passage downstream of the first stage. The first-stage turbine was then investigated over a range of speed from 20 to 130 percent of design and over a range of stage total-pressure ratio from 1.2 to 3.0. Turbine-gas inlet conditions were maintained at the values used in the multistage investigations (refs. 1 and 2). The over-all results are presented herein in terms of brake internal efficiency and equivalent work output (both based on torque measurements), equivalent weight flow, equivalent rotor speed, and equivalent stage total-pressure ratio. Results are tabulated in table I for the convenience of the reader.

SYMBOLS

The following symbols are used in this report:

E enthalpy drop based on torque measurements, Btu/lb

g gravitational constant, 32.174 ft/sec^2

N rotational speed, rpm

p static pressure, in. Hg abs

p' total pressure, in. Hg abs

p'_x static pressure plus velocity pressure corresponding to axial component of velocity, in. Hg abs

R gas constant, 53.345 ft-lb/(lb)(°F)

T' total temperature, $^{\circ}R$

w weight flow, lb/sec

$\frac{wN}{60\delta}\epsilon$ weight-flow parameter based on equivalent weight flow and equivalent rotor speed

γ ratio of specific heats

δ ratio of inlet-air pressure to NACA standard sea-level pressure, $p_1'/29.92$ in. Hg abs

ϵ function of γ, $\frac{\gamma_0}{\gamma_e}\left[\frac{\left(\frac{\gamma_e+1}{2}\right)^{\frac{\gamma_e}{\gamma_e-1}}}{\left(\frac{\gamma_0+1}{2}\right)^{\frac{\gamma_0}{\gamma_0-1}}}\right]$

η_i brake internal efficiency, defined as ratio of actual turbine work based on torque measurements to ideal turbine work based on inlet total pressure p_1' and discharge total pressure corrected for whirl $p_{x,2}'$

θ_{cr} squared ratio of critical velocity to critical velocity at NACA standard sea-level temperature of 518.4° R, $\frac{\frac{2\gamma}{\gamma+1}\, gRT'}{\frac{2\gamma_0}{\gamma_0+1}\, gRT_0'}$

τ torque, ft-lb

Subscripts:

cr critical

e engine operating conditions

h hub

t tip

x axial

0 standard sea-level conditions

1 turbine-inlet measuring station

2 turbine-outlet measuring station

APPARATUS AND INSTRUMENTATION

Apparatus

The standard-bladed multistage turbine from the J73 turbojet engine is described in detail in reference 1. For the present investigation, however, the second-stage rotor disk and stator were removed. The flow passage was modified to provide an annular discharge section behind the first stage of the turbine. This adapter section then permitted the gas to discharge into the standard turbine tail cone. A schematic diagram of the single-stage turbine assembly is presented in figure 1. A 20-mesh screen was installed on the upstream side of the flow-straightening tubes in an effort to minimize the circumferential pressure gradients observed in references 1 and 2.

The air-supply and exhaust systems to the first-stage turbine were the same as those described for the investigations of the multistage turbines (refs. 1 and 2). Turbine power was again absorbed by two cradled dynamometers connected in tandem. A photograph showing the set-up used for this investigation is presented in figure 2.

Turbine Instrumentation

The instrumentation required for the determination of the performance of the first-stage standard model turbine was essentially the same as that utilized for the multistage-turbine investigations (refs. 1 and 2). The gas state was measured at the two axial stations shown in figure 1, station 1 being upstream of the first stator and station 2 being downstream of the first rotor. Three total-pressure rakes, each consisting of three tubes located at area centers of equal annular areas, were mounted at station 1 (see fig. 1) at different circumferential locations. Turbine-inlet static pressures were measured by 22 taps, half on the inner wall and half on the outer wall, which were spaced around the annulus and diametrically opposed. The turbine-inlet temperature was measured by two calibrated spike-type thermocouple rakes, each consisting of five thermocouples located at area centers of equal annular areas. The two rakes were installed approximately 180° removed from each other.

At the turbine-outlet measuring station (station 2, fig. 1), three Kiel-type total-pressure tubes, a rake of five thermocouples radially spaced similarly to those at station 1, and four static taps on both the inner and outer walls were provided. The latter were spaced 90° apart and the taps on the inner and the outer walls were again diametrically opposed. This instrumentation was incorporated in order to duplicate interstage instrumentation that was installed for the multistage-turbine investigations (refs. 1 and 2), although this particular instrumentation was not described in the references.

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All turbine pressures were indicated on mercury manometers. Gas temperatures were taken with calibrated iron-constantan thermocouples in conjunction with a potentiometer. For convenience, and to expedite turbine operation and performance calculations, the thermocouples at each measuring station were arranged so that they could be connected in parallel; thus, either individual readings or the average of several readings could be observed. The turbine speed, the torque output, and the air weight flow were measured in the same manner as reported in references 1 and 2.

PROCEDURE

Turbine-inlet total pressure p_1' was calculated by the method outlined in reference 1. Turbine-outlet total pressure was determined at station 2 and is defined as the static pressure plus the velocity pressure corresponding to the axial component of the absolute velocity. This calculated value of turbine-outlet total pressure $p_{x,2}'$ charged the turbine for the kinetic energy of the rotor-exit tangential velocity component. Hence, the first-stage turbine efficiencies as computed and presented herein are considered conservative.

The single-stage turbine was operated at constant nominal inlet values of pressure and temperature corresponding to 35 inches of mercury absolute and 700° R, respectively. The unit was operated over a range of speed from 20 to 130 percent of the design equivalent value (4041 rpm) and over a range of stage pressure ratio $p_1'/p_{x,2}'$ from 1.2 to approximately 3.0.

RESULTS AND DISCUSSION

The over-all performance of the first stage of the standard-bladed J73 turbine is presented in a manner similar to that used to show the multistage-turbine performance (refs. 1 and 2). Data are presented in table I for convenience, and also in graphs. The performance map (fig. 3) shows the single-stage performance in terms of equivalent shaft work

$E/\theta_{cr,1}$ and a weight-flow parameter $\frac{wN}{60\delta}\,\epsilon$ for lines of constant equivalent rotor speed $N/\sqrt{\theta_{cr,1}}$, constant equivalent stage total-pressure ratio $p_1'/p_{x,2}'$, and contours of brake internal efficiency η_i. (All performance parameters are corrected to NACA standard sea-level inlet conditions corresponding to 29.92 in. Hg abs and 518.4° R.) The peak efficiency of over 90 percent observed for the turbine occurred near an over-all stage pressure ratio of 1.4 and at 90 percent of the design equivalent speed. It is also apparent from figure 3 that the turbine had a high efficiency over a relatively wide operating range. 3209

The performance map (fig. 3) was constructed from faired values of the measured equivalent weight flow $\frac{w\sqrt{\theta_{cr,1}}}{\delta_1}\,\epsilon$ and equivalent torque output $\frac{\tau}{\delta_1}\,\epsilon$. The variation of the equivalent weight flow with over-all stage pressure ratio for the various rotor speeds is presented in figure 4, which indicates that the turbine stator is choked for all values of speed at a pressure ratio of approximately 2.3 and above. The observed choking value of equivalent weight flow was 42.65 pounds per second.

The variation of equivalent torque with over-all stage pressure ratio is shown in figure 5. At the higher speeds and pressure ratios, the slope of the torque curves is small, which indicates that the turbine is operating near limiting blade loading.

Although the first stage of the J73 standard-bladed turbine was investigated over a range of stage pressure ratio from 1.2 to 3.0, it is deemed important to state that the unit does not operate over this entire range when incorporated in the multistage unit. At design speed and work output, the over-all total-pressure ratio for the standard-bladed multistage turbine was 2.75 and the measured first-stage pressure ratio was 1.62 as determined from the aforementioned interstage instrumentation. At this measured value of first-stage pressure ratio and from the single-stage turbine investigation, the calculated stage pressure ratio $p_1'/p_{x,2}'$ was 1.61. The latter value is thus considered to be the design value for the pressure ratio of the first stage of the turbine. From the performance map (fig. 3), it can readily be seen that the unit is operating at a brake internal efficiency of over 89 percent at this design stage pressure ratio and speed. Furthermore, the first-stage turbine would produce an equivalent shaft work output of approximately 14.22 Btu per pound at this stage pressure ratio of 1.61. Since the design work of the multistage turbine was considered to be 28.48 Btu per pound, and the first stage of the turbine is assumed to be operating at the aforementioned conditions, it is apparent that the first stage of the multistage turbine produced approximately 50 percent of the total work output at the design operating point.

SUMMARY OF RESULTS

From an investigation of the over-all performance of the first stage of the standard-bladed multistage J73 turbine, the following results were obtained:

1. A peak brake internal efficiency of over 90 percent was obtained at an over-all stage pressure ratio of 1.4 and 90 percent of
3209 equivalent design rotor speed.

2. The turbine exhibited a wide range of efficient operation.

3. At the design operating point of the multistage turbine, the first stage produced approximately 50 percent of the total turbine work output.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 11, 1953

REFERENCES

1. Berkey, William E., Rebeske, John J., Jr., and Forrette, Robert E.: Performance Evaluation of Reduced-Chord Rotor Blading as Applied to J73 Two-Stage Turbine. I - Over-All Performance with Standard Rotor Blading at Inlet Conditions of 35 Inches of Mercury Absolute and 700° R. NACA RM E52G31, 1957.

2. Schum, Harold J., Rebeske, John J., Jr., and Forrette, Robert E.: Performance Evaluation of Reduced-Chord Rotor Blading as Applied to J73 Two-Stage Turbine. II - Over-All Performance at Inlet Conditions of 35 Inches of Mercury Absolute and 700° R. NACA RM E53B25, 1957.

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TABLE I. - DATA SUMMARY FROM EXPERIMENTAL INVESTIGATION OF J73 MODIFIED FIRST-STAGE TURBINE WITH STANDARD ROTOR BLADING

Calculated over-all total-pressure ratio, $p_1'/p_{x,2}'$	Over-all total-pressure ratio, p_1'/p_2'	Over-all total-to-static pressure ratio at hub, $p_1'/p_{h,2}$	Over-all total-to-static pressure ratio at tip, $p_1'/p_{t,2}$	Inlet total pressure, p_1', in. Hg abs	Inlet total temperature, T_1', $^{\circ}R$	Outlet total temperature, T_2', $^{\circ}R$	Engine speed, N, rpm	Weight flow, w, lb/sec	Torque, τ, ft-lb
1.107	1.096	0.885	0.884	34.75	700.8	689.0	942	30.48	720
1.145	1.145	.858	.854	34.91	700.8	678.7	2824	29.80	442
1.145	1.140	.858	.875	34.88	700.8	678.7	3302	29.20	350
1.148	1.134	.854	.856	34.97	700.8	681.0	3775	28.89	294
1.239	1.172	.770	.785	34.82	701.3	680.6	940	38.27	1356
1.235	1.217	.780	.776	34.72	701.3	669.5	1888	37.72	1117
1.238	1.257	.784	.776	34.73	701.2	684.1	2835	36.36	853
1.230	1.228	.790	.785	34.86	701.0	666.1	3522	35.00	671
1.237	1.232	.787	.781	34.88	701.0	665.1	3772	34.59	597
1.244	1.234	.781	.778	34.89	701.0	666.2	4246	34.53	526
1.247	1.220	.777	.781	34.94	701.0	668.5	4731	34.07	421
1.436	1.282	.844	.667	34.69	702.5	672.1	945	41.87	1965
1.453	1.359	.644	.646	34.67	701.5	656.3	1875	41.84	1768
1.437	1.398	.660	.648	34.73	701.5	645.4	2841	41.53	1473
1.392	1.382	.686	.674	34.70	701.5	646.7	3501	40.43	1198
1.388	1.388	.688	.677	34.72	701.4	644.5	3774	39.89	1075
1.388	1.389	.689	.679	34.81	701.4	644.5	4241	39.44	934
1.394	1.389	.686	.677	34.75	701.4	644.5	4724	38.94	822
1.406	1.392	.679	.674	34.65	701.3	645.7	5193	38.66	737
1.411	1.386	.674	.673	34.76	700.3	647.9	5654	38.61	642
1.418	1.364	.669	.675	34.72	701.3	651.5	6139	38.28	540
1.593	1.412	.564	.591	34.64	702.5	666.6	946	42.20	2270
1.555	1.434	.595	.599	34.79	701.6	651.8	1891	42.09	1963
1.527	1.503	.624	.604	34.78	702.5	637.3	2830	42.10	1646
1.522	1.501	.621	.608	34.78	702.5	634.3	3500	41.90	1523
1.529	1.523	.619	.605	34.79	701.5	630.0	3774	41.72	1393
1.516	1.516	.625	.613	34.79	701.5	631.8	4243	41.15	1224
1.519	1.518	.624	.611	34.79	701.5	630.8	4720	40.92	1104
1.522	1.512	.614	.611	34.71	701.5	629.9	5186	40.54	978
1.525	1.519	.621	.611	34.75	701.5	631.9	5657	40.31	872
1.533	1.513	.614	.610	34.81	701.4	635.2	6131	40.16	766
1.879	1.577	.460	.484	34.72	702.6	661.0	941	42.50	2636
1.766	1.587	.506	.517	34.78	701.8	641.7	1882	42.56	2280
1.706	1.661	.540	.531	34.64	701.6	627.0	2852	42.36	1914
1.693	1.668	.550	.535	34.71	701.6	619.7	3296	42.34	1787
1.675	1.666	.557	.542	34.75	701.5	618.4	3775	42.27	1653
1.683	1.693	.556	.537	34.76	701.5	615.2	4246	42.23	1520
1.690	1.703	.652	.536	34.78	701.5	614.1	4716	42.09	1396
1.686	1.692	.554	.538	34.72	701.5	614.2	5198	41.80	1259
1.684	1.691	.558	.539	34.75	701.5	614.1	5658	41.62	1125
1.688	1.645	.552	.569	34.76	701.5	616.3	6130	41.43	1020
2.231	1.714	.375	.377	34.85	701.5	657.2	937	42.55	2917
2.062	1.801	.414	.424	34.82	701.6	631.0	1886	42.57	2569
1.968	1.803	.454	.446	34.76	701.5	611.6	2823	42.53	2217
1.919	1.862	.472	.457	34.71	701.6	608.5	3290	42.53	2062
1.901	1.862	.481	.461	34.72	701.5	602.3	3763	42.40	1921
1.910	1.892	.480	.458	34.68	701.6	598.0	4247	42.40	1798
1.918	1.922	.480	.455	34.74	701.5	594.8	4722	42.35	1692
1.875	1.860	.480	.475	34.80	701.5	598.9	5193	42.32	1506
1.877	1.864	.490	.470	34.72	701.5	597.9	5659	42.18	1375
1.892	1.878	.486	.465	34.73	701.5	597.9	6135	42.15	1259
2.390	1.785	.348	.340	34.70	701.6	628.1	1888	42.53	2763
2.248	1.905	.380	.375	34.71	701.6	602.0	2825	42.53	2407
2.199	1.961	.395	.392	34.77	701.5	595.3	3299	42.51	2298
2.194	2.056	.400	.382	34.71	701.5	588.6	3772	42.51	2150
2.147	2.035	.415	.393	34.72	701.5	584.3	4246	42.48	2006
2.137	2.059	.420	.394	34.68	701.5	582.0	4721	42.39	1879
2.098	2.043	.431	.404	34.61	701.6	577.7	5211	42.41	1717
2.109	2.071	.426	.401	34.59	701.6	580.6	5662	42.38	1576
2.110	2.069	.428	.401	34.69	701.6	578.6	6130	42.39	1463
2.628	1.998	.302	.293	34.64	701.6	596.1	2829	42.51	2562
2.563	2.079	.317	.305	34.68	701.6	586.6	3293	42.49	2449
2.559	2.202	.320	.304	34.70	701.6	579.2	3773	42.57	2294
2.481	2.234	.337	.319	34.69	701.7	573.7	4242	42.54	2195
2.478	2.250	.342	.318	34.74	701.6	569.5	4714	42.54	2079
2.459	2.298	.348	.318	34.74	701.6	567.2	5196	42.58	1946
2.418	2.312	.360	.327	34.80	701.6	566.7	5658	42.54	1776
2.405	2.317	.362	.329	34.75	701.6	567.7	6129	42.49	1660
2.823	2.181	.270	.250	34.70	701.6	585.2	3295	42.61	2498
2.876	2.286	.266	.238	34.74	701.6	577.1	3770	42.61	2571
2.908	2.359	.261	.231	34.63	701.6	570.0	4232	42.54	2273
2.750	2.370	.290	.264	34.70	701.6	564.5	4711	42.49	2143
2.688	2.414	.302	.275	34.87	701.6	561.1	5183	42.50	2012
2.655	2.458	.312	.278	34.73	701.6	561.8	5654	42.49	1875
2.591	2.443	.325	.291	34.74	701.6	562.5	6134	42.41	1727
2.948	2.434	.256	.223	34.61	701.6	565.0	4713	42.44	2156
2.982	2.501	.253	.213	34.59	701.6	560.0	5185	42.48	2026
3.021	2.582	.249	.200	34.65	701.6	558.0	5647	42.48	1910
3.080	2.635	.240	.183	34.68	701.5	556.1	6126	42.48	1773

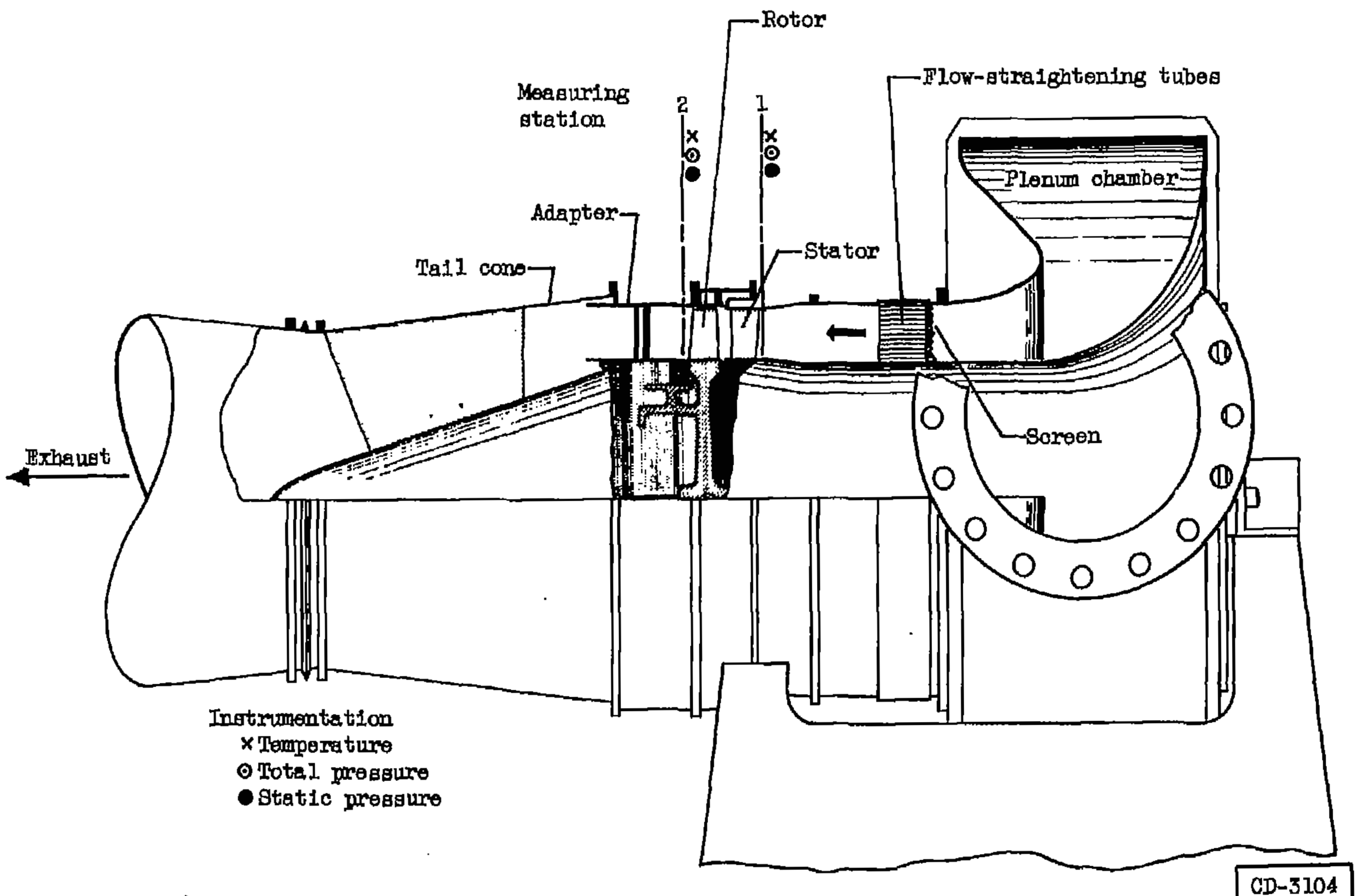

Figure 1. - Schematic diagram of single-stage-turbine assembly and instrumentation.

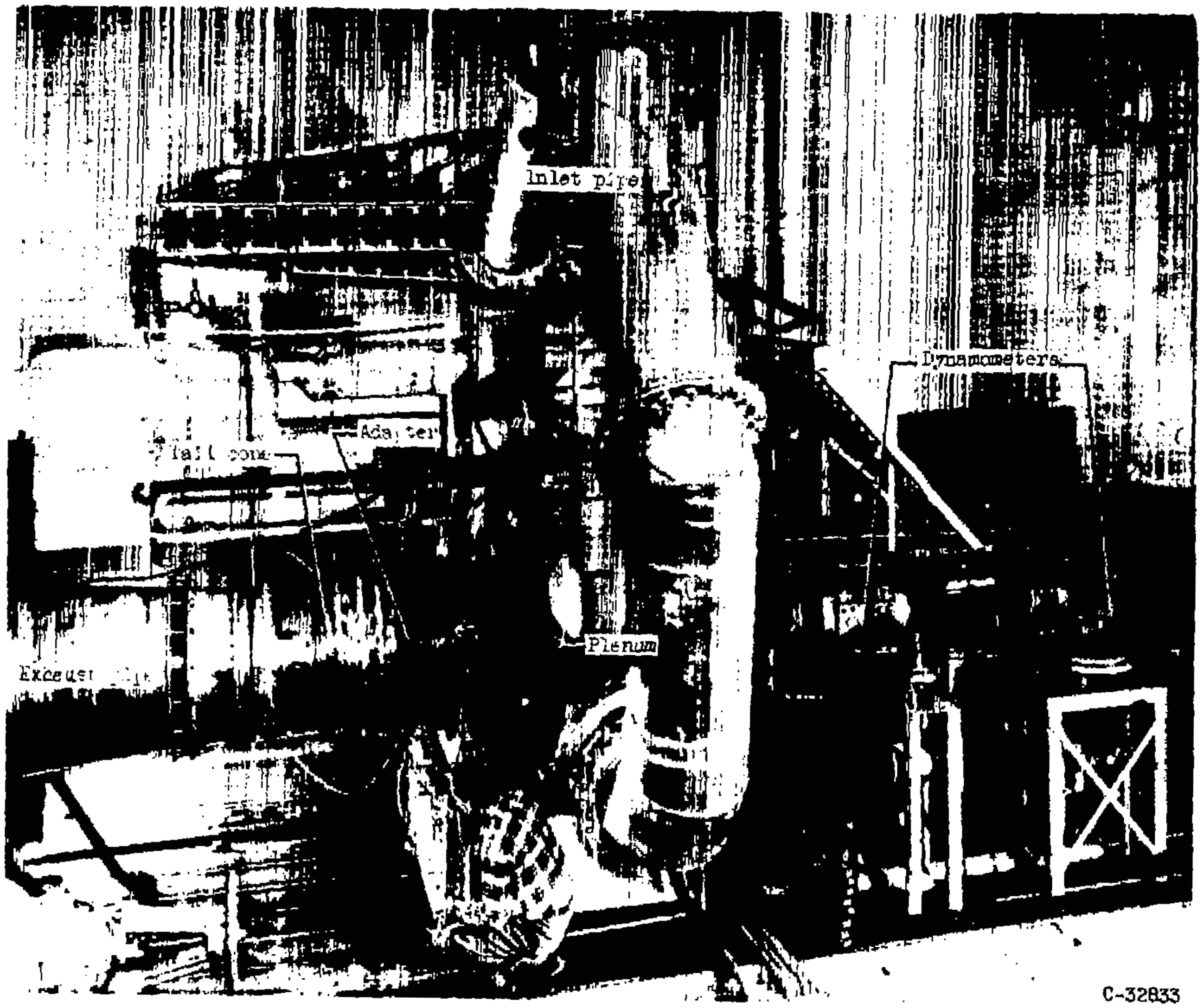

Figure 2. - Setup for investigation of performance of J73 single-stage turbine equipped with standard rotor blading.

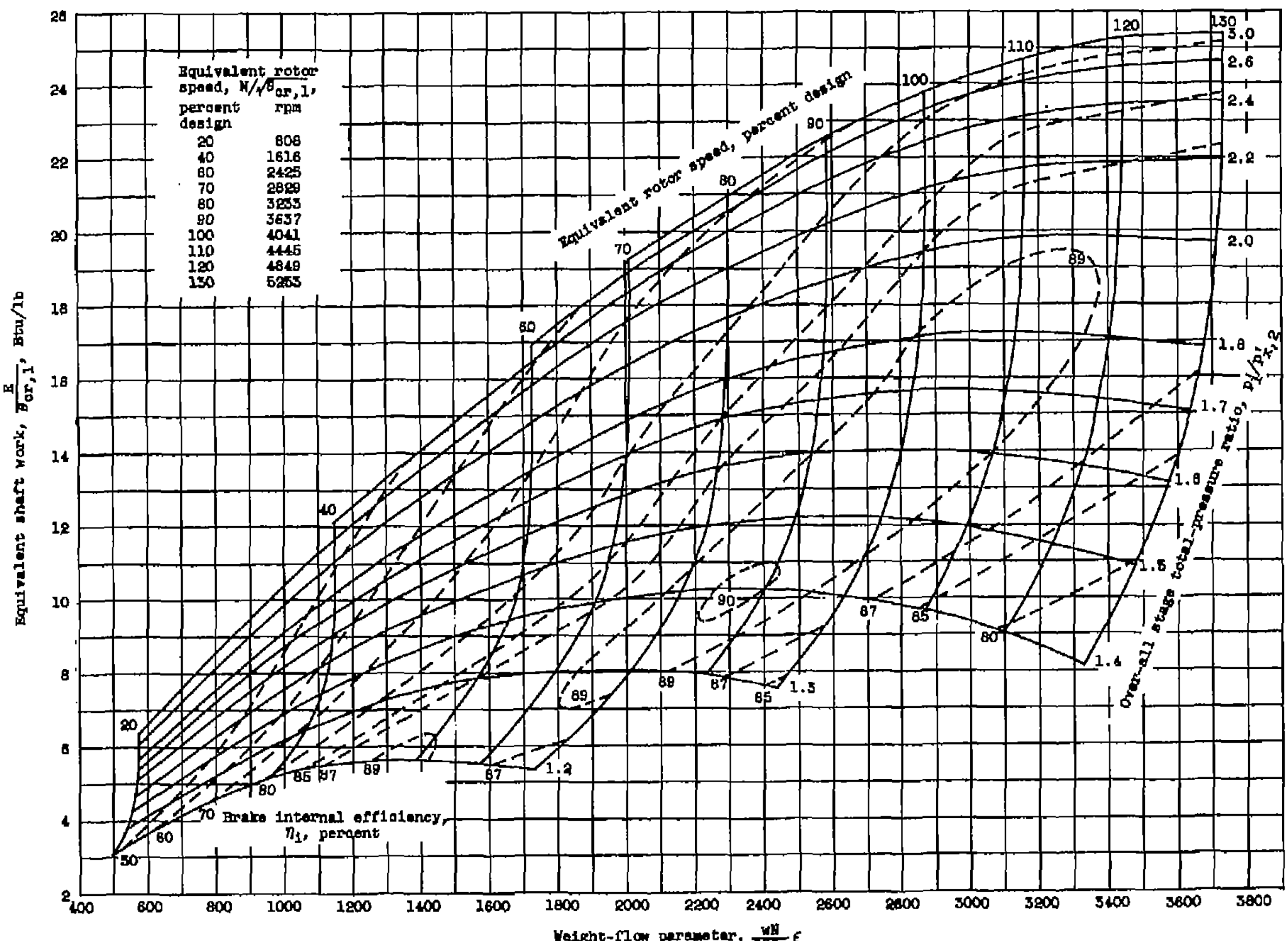

Figure 3. - Over-all performance of J73 modified single-stage turbine equipped with standard rotor blading. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

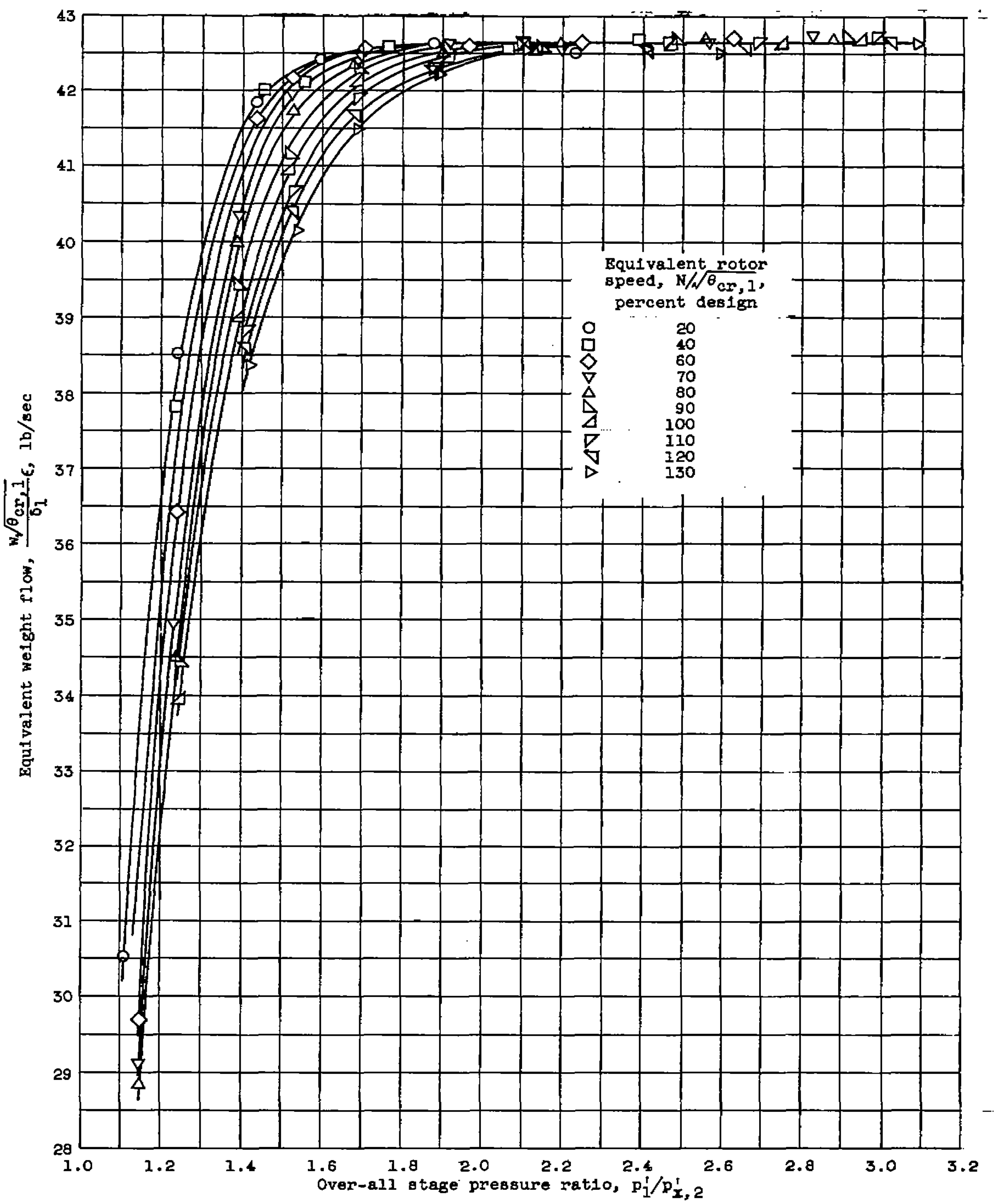

Figure 4. - Variation of equivalent weight flow with over-all stage pressure ratio at different speeds for J73 modified single-stage turbine equipped with standard rotor blading.

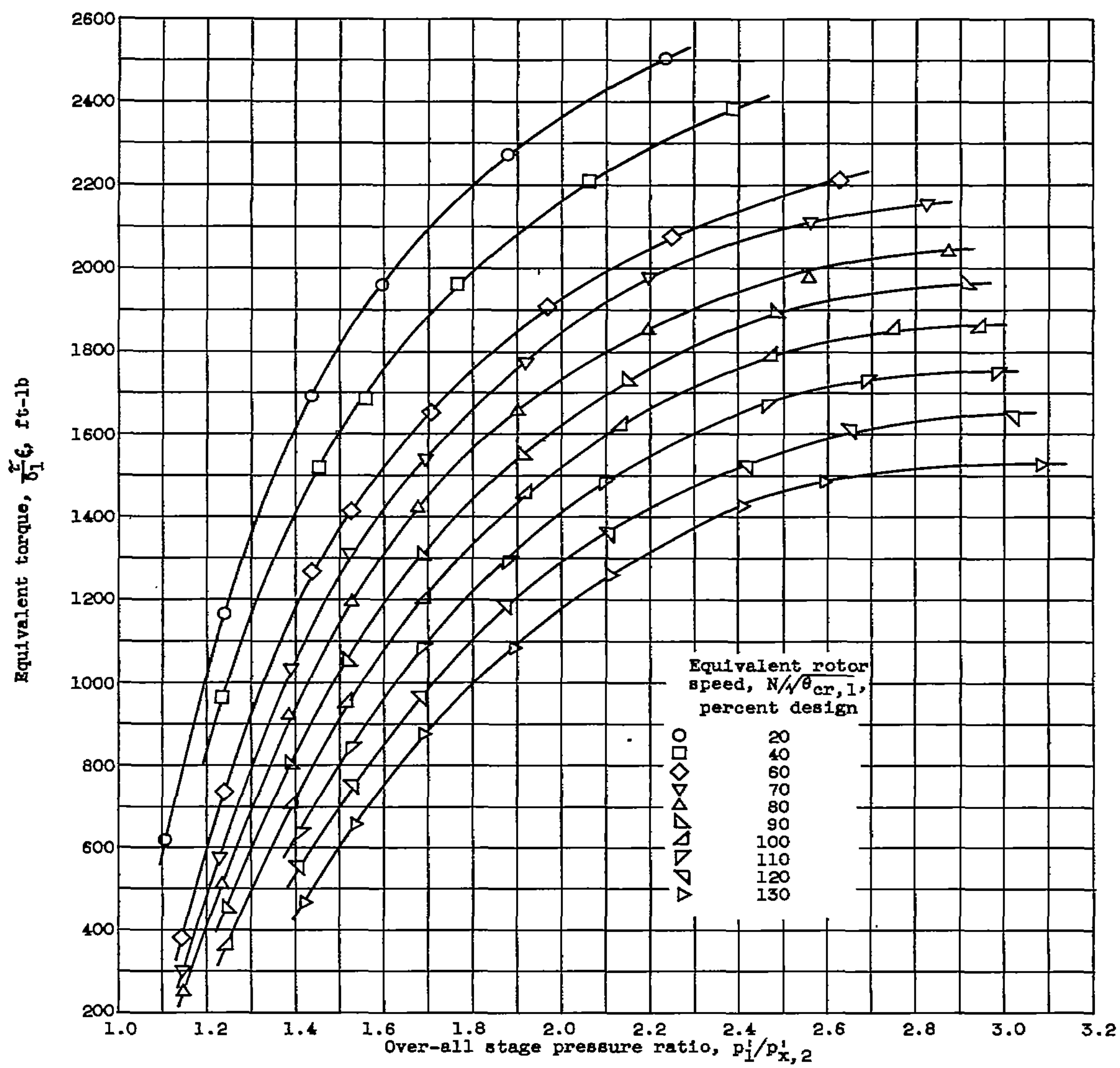

Figure 5. - Variation of equivalent torque with over-all stage pressure ratio at different speeds for J73 modified single-stage turbine equipped with standard rotor blading.

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